

A SURFACE MICROMACHINED, OUT-OF-PLANE ANEMOMETER

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1. SUMMARY

A novel out-of-plane hot-wire anemometer has been developed by combining surface micromachining and efficient three-dimensional assembly. The sensing filament is made of metal instead of doped silicon. It is elevated from the substrate using an efficient three-dimensional assembly process, resulting in greater sensitivity. The overall process temperature is low ($<250^{\circ}\text{C}$). Hence the process can be realized on non-silicon, low-cost and flexible substrates. Time constant in constant-current mode is found to be below 50- μs with a wire thickness of 1000 Å and 50- μm in length.

2. BACKGROUND

Commercial flow sensors are mainly based on two principles: (1) Hot-Wire Anemometry (HWA) and (2) Laser-Doppler Velocimetry (LDV). A thermal anemometer consists of a heated element, which also function as a temperature sensor. As flow passes the anemometer element, heat is transferred to the fluid media via forced convection, effectively reducing the temperature of the probe. The flow speed is derived indirectly from the temperature variation from the steady state values.

Commercial hot wire anemometers typically achieve a flat frequency response from 0 to 20-50 kHz. The sensing filament has a diameter of approximately 5- μm and length of 1.25-mm[1]. The filament is typically made of platinum or tungsten due to the high temperature coefficient of resistance (TCR). Doppler frequency-shift effect can be used to monitor the speed of traveling fluid media. The amount of flow rate is deduced from the extent of frequency shift. Such system provides anemometry with greater accuracy, wider velocity range (up to 1000 m/s), and versatility in a wide variety of fluid flow. However, it has poor spatial resolution, and a lower frequency response[1].

3. MICROMACHINED FLOW SENSORS

Micromachined anemometers have been studied in the past by several groups [2-4]. Micromachining has the potential to provide several improvements over the current commercial flow sensors. The batch processing nature of micromachining will not only reduce cost, but it can provide greater uniformity. In addition, the sensing

filament can have faster frequency response due to smaller dimensions. For example, anemometers with polysilicon hot-wire and bulk-micromachined support beams have achieved a time constant of 2- μs [2]. Another HWA [3] made by combining bulk micromachining and polyimide-joint assembly can measure flow on 3-axis. Surface micromachined anemometer has also been made on a polymer substrate[4]. However, they suffer from some trade-off.

HWA fabricated using bulk micromachining of silicon substrates [2-3] allows large distance between the sensing wire and the substrate. This will increase thermal insulation to the substrate and hence increase the sensitivity. However, bulk micromachining incur higher cost and place restriction on the type of substrate that is used.

HWA made using surface micromachining does not have the restriction on the substrate material and the sensing element. The fabrication process is simpler. However, the sensing wire is either situated directly on the substrate or very close to it. This leads to a slower frequency response and reduced sensitivity.

In addition, many devices use doped polysilicon thin film as the material for hot-wires. The polysilicon deposition and annealing require a high-temperature process and generally preclude the use of substrates with low melting point.

4. PRINCIPLE AND DESIGN

In this work we sought to improve the design and fabrication of HWA by (1) using an efficient three-dimensional assembly process in conjunction with a surface micromachining process to avoid costly and time-consuming bulk micromachining steps; (2) using metal thin film (nickel and platinum) as the hot-wire element instead of polysilicon.

Surface micromachining is advantageous over bulk micromachining as discussed above. However, the sensitivity and response time would suffer if the hot-wire element is located next to the substrate. Flow rate at the interface of the substrate and the fluid environment is zero based on non-slip boundary conditions. In order to increase the sensitivity, it is important to lift the hot-wire element away from the immediate boundary, such that

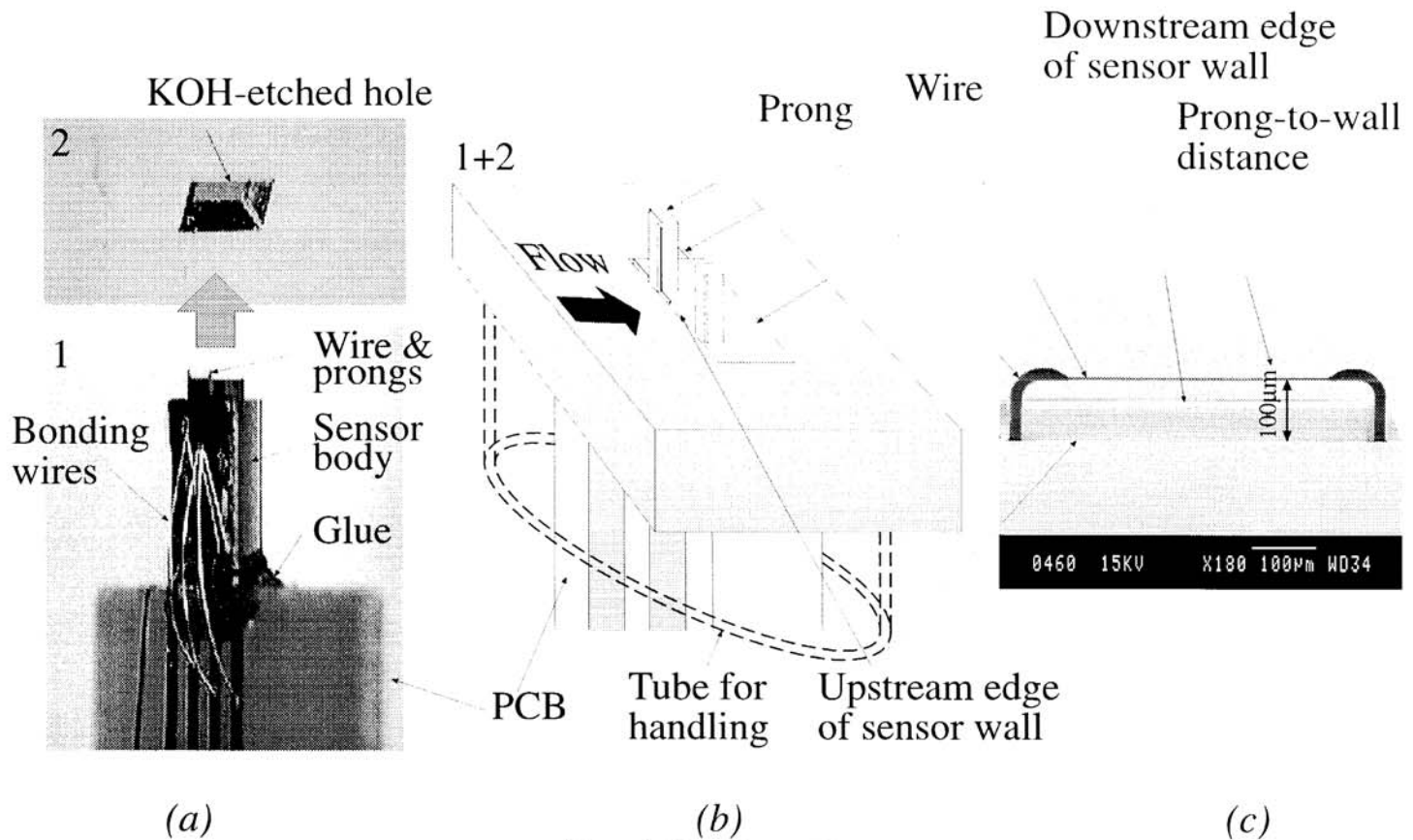


Figure 1: Hybrid assembly

Left: The sensing chip glued and wire bonded to the tip of a PCB is inserted in the KOH-etched hole in the holding chip.

Middle: After insertion the "sensor wall" is in-plane with the holding chip wall.

Right: SEM micrograph of the front of an assembled sensor.

Our selection of the hot-wire material is aluminium. This differs from most other MEMS hot-wire anemometers and enables us to use the sensor with standard CTA measuring equipment. Aluminium is not used for conventional hot-wires, because of the difficulty in welding or soldering it to the prongs. In micromachining, however, the processing of aluminium is fairly uncomplicated. Data shows that the performance of aluminium wires is as good as conventional hot-wires both in terms of the temperature coefficient of resistivity (0.0038 K^{-1} against 0.0036 K^{-1} for tungsten) and in terms of thermal conductivity (235 W/m-K against 170 W/m-K).

DESIGN

Several versions have been fabricated. The sizes of the fabricated hot-wires range from $1\mu\text{m} \times 2\mu\text{m} \times 200\mu\text{m}$ to $3\mu\text{m} \times 2\mu\text{m} \times 600\mu\text{m}$. The wire is held up at distances ranging from $50\mu\text{m}$ to $250\mu\text{m}$ from the surface by a pair of prongs with a cross section of $20\mu\text{m} \times 20\mu\text{m}$. (See Figure 1c & Figure 3.) The sensor chip is attached and wire-bonded to a PCB. This is then positioned in a KOH-etched hole in a cover chip. The size of the hole is such that there is less than $5\mu\text{m}$ of space between the sensor chip and the cover chip. The cover chip is $20\text{mm} \times 20\text{mm}$ in size and $300\mu\text{m}$ thick. These outer dimensions were designed for our

measurement setup, but we can easily vary the outer dimensions of the cover chip by dicing it differently. A tube glued to the back side of the cover chip which filled up with filling epoxy facilitates handling. (See Figure 1b.) The entire setup is placed in a plexiglass chuck which, in turn, is placed in the wall of the wind tunnel.

The maximum step introduced in the system besides the prongs is $10\mu\text{m}$. The gap between the sensor chip and holding chip is bridged by the glue, which is pulled to the correct position by capillary forces. The prongs are curved inwards to ease insertion, i.e. they provide a margin for movement when the chip is being positioned. The rhomboidal shaped hole in the holding chip gives extra maneuvering space without compromising the hole size on the front.

FABRICATION

The total fabrication can be divided into two parts; a MEMS part where the sensor and cover chips are processed, and a hybrid part, where the sensor chip is inserted into the cover chip:

1. MEMS fabrication

A bulk micromachining process is used to form the hot-wire probe. The fabrication is performed on a 100mm diameter (100) Silicon-on-insulator (SOI) wafer

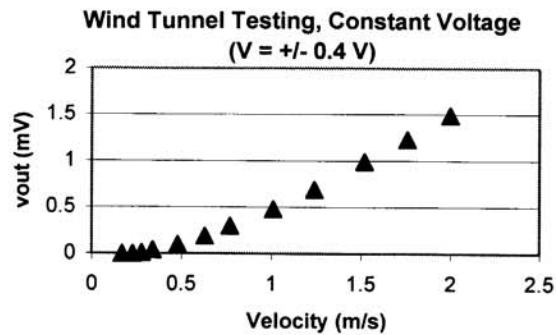


Figure 7: Wind tunnel testing output with a 0.4 V bias being applied across a Type-2 anemometer and a calibrating potentiometer.

The thermal response time is short due to the low thermal mass of the heating element. Time-constant measurements have been performed on two types of devices with different sensor geometry (Fig. 8-9). Figure 8 illustrates the captured time-domain response when a square-wave current is applied to the hot-wire sensor. The output response is used to identify the time constant. The lowest time constant observed is 23- μ s for a 50- μ m-long Type-2 anemometer in constant current operation. The comparison of time constants for the two types fabricated sensors is shown in Fig. 9.

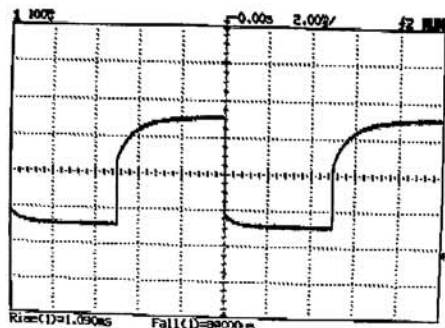


Figure 8: Square wave response of a 150- μ m-wide anemometer.

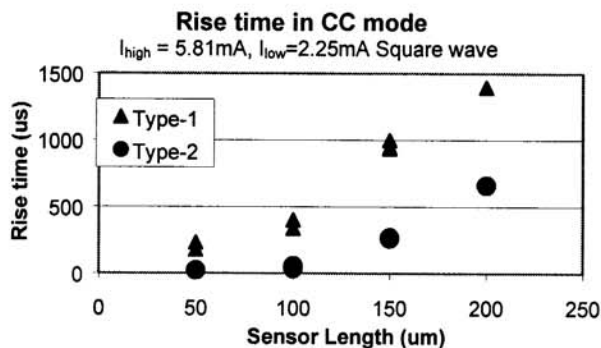


Figure 9: Experimentally measured rise time for two types of anemometers with different hot-wire lengths. Type-2 devices have faster response by not using polyimide in the support beams and hot-wire sensor.

6. CONCLUSIONS

We have successfully developed a micromachined hot-wire anemometer. The anemometer is made of metal and is constructed using a monolithic three-dimensional assembly method and employs a low-temperature process. Further improvement will involve strengthening the deformed beam and the use of platinum as sensing filament. Constant temperature circuit will also be considered.

7. ACKNOWLEDGEMENTS

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